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The strain fields present during the bending of ultra-high strength steels

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Abstract

Ultra high strength steels (UHSS) have an ultimate tensile strength of greater than 1GPa. Typically, their ambient temperature elongation is less than 10% and as a result, they are rarely used in stamping applications. However, the continuous demand for the weight reduction of structures built for the transport sector means that such materials are attractive because they can be used for parts with thinner cross-sections while maintaining required in-service performance. One way to overcome the ambient temperature ductility of these materials is to roll-form them, particularly with emerging flexible roll forming technology. Using numerically-controlled actuators, the rolls on each stand are designed with sufficient degrees of freedom to form parts that curve, vary in depth and width along their lengths. This makes flexibly roll-formed parts attractive to the transport, particularly the automotive, sector. Roll forming deforms a material through incremental, localised bending, which is known to suppress the necking response, resulting in deformations that are higher than in stretch deformation. Recent work, such as Le Maoût, Thuillier & Manach, *Eng. Frac. Mech.*, Vol. 76, p.1202 (2009), focussed on the development of ductile fracture models to explain failure but their validation was limited to load displacement and surface strain data. This work aims to characterise the strain field during bending more comprehensively. Using the digital image correlation technique, the macroscopic strain distribution in UHSS in the thickness of the sheet and the strain partitioning in its microstructure is measured during bending. The data provides a detailed explanation of the strain distribution during bending.

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1. Introduction

There is relentless pressure on transport manufacturers for environmentally friendly products that are safe. The contradictory demands are leading to ever increasing adoption of high strength materials that can be used to manufacture components with thinner walls rather than materials that have a lower density. However, high strength materials tend to be difficult to process at ambient temperatures so manufacturers, particularly, automotive manufacturers resort to warm and hot forming. With steels, boron steel blanks are heated up to 950°C and then stamped and quenched simultaneously at more than 30°/s to ensure the transformation from a soft austenitic structure to a fully hardened martensitic structure. The resulting part has little springback and an ultimate tensile strength (UTS) of about 1.5GPa. However, such parts are costly because of the manufacturing energy required and the specialist joining techniques required for joining them to other parts of the structure.

An alternative strategy is to change the processing method so that the deformation mode to form a part becomes more favorable for the processing of low ductility materials. This paper will consider the processing of ultra-high strength steels (UHSS) using roll forming. Roll forming is commonly used to manufacture straight products with complex cross-sections. Rather than deforming a blank in stretch and draw, roll forming incrementally bends sheet as it flows through a set of rollers. The rollers are mounted on stands and the number of stands required for a part depends on the complexity of its cross-sectional geometry. Typically, a roll forming line can have up to 35 stands. The bending deformation mode means that only a small portion of the blank is deformed compared to a stamping operation, resulting in low energy consumption. Currently, roll forming is not used widely for automotive applications because parts are restricted to straight geometries along its length. Recent advances in computing power and numerical control of actuators are leading to the emergence of flexible roll forming, which is able to manufacture parts that are not restricted to straightness along its length, making it more attractive for processing automotive structures.

Recent work on roll forming has looked into the effect of process parameters on residual stresses that cause defects and the development of models that predict the onset of failure during the bending operation. For example, Mendiguren *et. al* [1] and Weiss *et. al* [2] tried to relate defects in dual phase steels and aluminium respectively to the residual stresses in as-received sheet. Hosseini *et. al* [3] developed a strain gauge-based technique to measure residual stresses that cause flaring in UHSS parts. Le Maoût *et. al* [4] discussed the development of a ductile fracture criterion to predict failure and compared aspects of the model's prediction against visual inspection of physical samples. Although stresses and strains are responsible for the occurrence of defects (such as springback and flare) and failure, the underlying strain fields generated during incremental bending are not well understood. In this work, the digital image correlation (DIC) technique was used to characterise these underlying full-field strains more closely. Ideally, it would have been desirable to measure these strains during a roll-forming operation. However, because of the complexity of the mesurments and the limited availability of a roll forming line, the measurements were carried out in three experiments. Strains were measured through the thickness of the sheet, on the top surface of sheet during incremental bending and the partitioning of strains within the microstructure of the sheets. The investigation was carried out on a UHSS dual phase grade and the resulting measurements revealed the strain distributions that occur in UHSS during incremental bending.

2. Method

The chemical composition of the dual phase UHSS is given in Table 1.

Element	C	Mn	Si	Nb
Composition %	0.15	0.15	0.05	0.013

Table 1 Chemical composition of the dual phase grade

Macroscopic strains were measured using a GOM Aramis digital image correlation (DIC) instrument. The instrument consisted of two 12 Megapixel sensors that captured images of deforming samples and a software module that analysed the images and calculated the strains on the sample surface. Samples were prepared by applying a fine speckled pattern to their surfaces which the cameras tracked. The software then calculated the strains based on the motion of the pattern as the samples deformed. Microscopic strains were measured in 2 stages. In the first stage, the sample was mounted on a 'mechanical' stage that was mounted in a Zeiss Sigma FEG-SEM. The sample was deformed in the SEM and its deformation was captured by the SEM. The images were then transferred to a PC and the microscopic DIC analysis was carried out using LaVision software. No additional preparation was required of the samples. The software used the natural optical contrast present in the microstructure to track its deformation. In was not possible to carry out the measurements in a single experiment. The samples were therefore bent in plane strain to measure through thickness strains, incrementally bent to measure surface strains and in tension in a SEM to measure the partitioning of strains within the microstructure. The area measured by the SEM was 50μm x 50μm and the results were taken to represent the strain partitioning within a layer of a bending sample.

Plane strain bending tests were carried out on a purpose built bending rig mounted on an Instron tensile testing machine. The sheet was clamped in the blankholder of the rig and the sheet was deformed with a vertically descending punch. The die radius was 3mm and the punch radius was 8mm. The DIC device was placed in front of the rig to capture strains along the thickness of the sheet (Fig.1). Three repeats were carried out. Measurement error for the DIC was estimated to be ±0.005 strain.

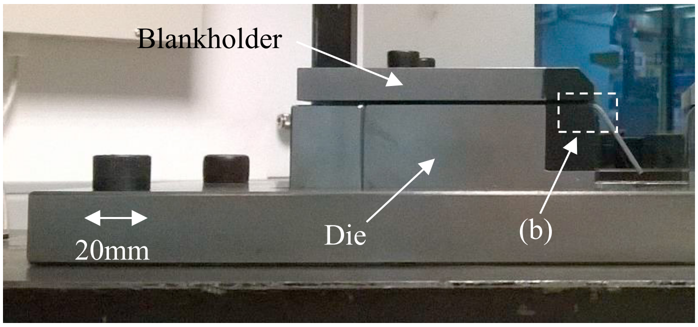


Fig.1(a) Photo of bending rig mounted on Instron 5800

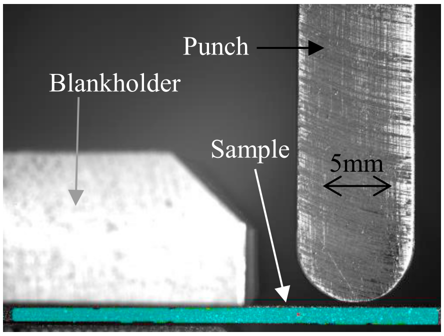


Fig.1(b) DIC measurement area showing the punch orientation

The incremental bending process that occurs during roll forming was simulated using roller hemming apparatus because of the unavailability of a roll forming line. A 40mm roller was mounted on a 6-axis robot and was programmed to deform a sample clamped in the tool shown in Fig.2. Macroscopic DIC measurements were taken at the top surface of the sample as the roller deformed it. Three repeats were carried out.

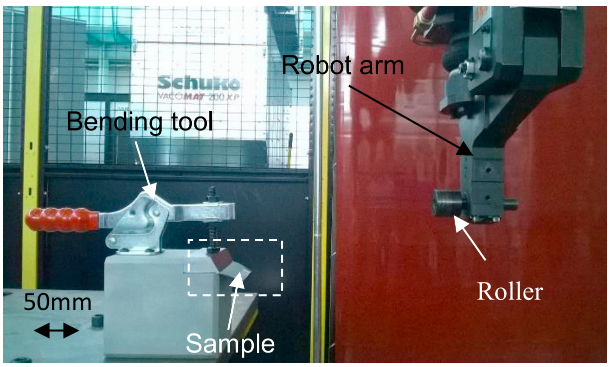


Fig.2 Apparatus for incremental bending

The microscopic DIC measurements were carried out on samples mounted on a Gatan *in-situ* tension rig shown in Fig.3. The tensile samples were 36 x 18 mm with a gauge area measuring 2mm x 2mm and were manufactured by wire-erosion. Rather than adopting straight edges, the gauge area was designed to be waisted so as to ensure that deformation took place in the middle of the gauge area. The sample was deformed in tension until failure and the rig was controlled remotely from outside the SEM chamber. Approximately 35 images were captured during the test. After the test, the images were transferred to a PC and the DIC was carried out with the LaVision software. Three repeats were carried out.

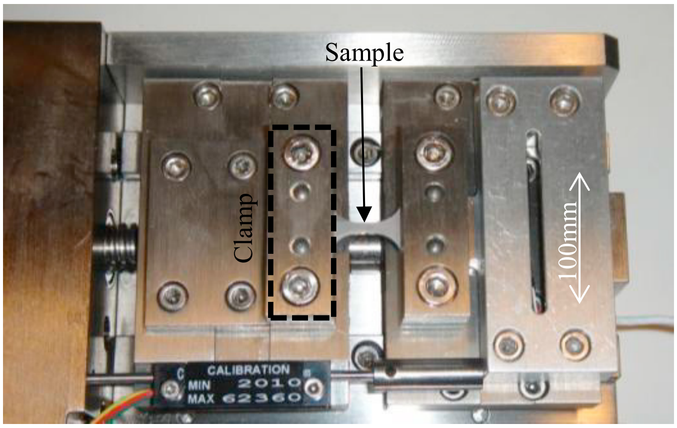
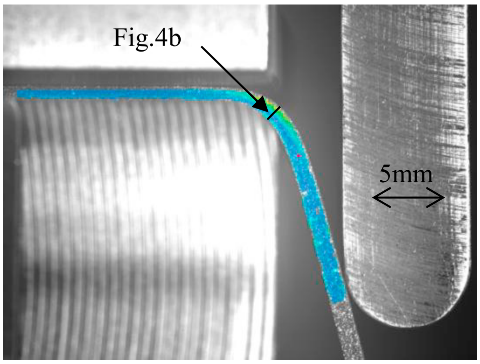


Fig.3 The Gatan tensile stage used for the microscopic DIC

3. Results

The results from the plane strain tests are shown in Fig.4.



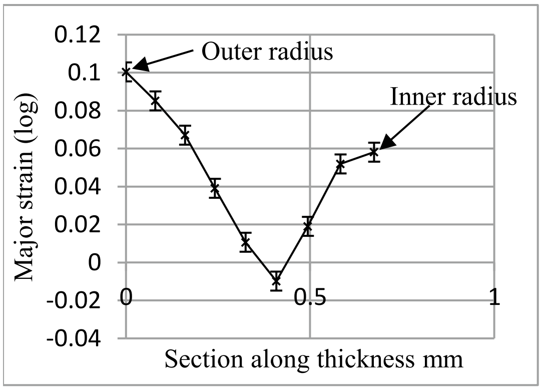


Fig.4(a) Contour plot of through-thickness major strain

Fig.4(b) Through thickness strain distribution

Fig.4a shows the contour plot of a sheet deformed in plane strain. The strain distribution (Fig.4b) varied from about 0.1 strain at the outer radius of the bend to slightly negative at 0.4mm from the outer radius and then became positive again towards the inner radius. The distribution is at odds with the assumption that the ligament of material at the inner radius should be in compression. The contradiction may be due to two reasons. First, frictional forces were present at the inner radius due to the contact of the ligament with the die radius and modified the strain distribution near the inner radius. Second, although the sheet was 1.2mm thick, Fig.4b shows data restricted to 0.7mm of sheet thickness because the bottom portion of the sheet was visually obscured by the die radius during the experiment.

Fig.5a shows a sample twisting along its length, the contour plot on the sheet and the position and loading of the roller on the sheet. Fig.5b shows lines indicating that the direction of the major strains on the surface of the sheet occurs out of its sheet thickness plane. This contrasts to plane strain bending, where deformation is restricted to the thickness plane of the sheet and may explain the increased formability that is frequently observed when bending sheet in an incremental manner such as in roll forming.

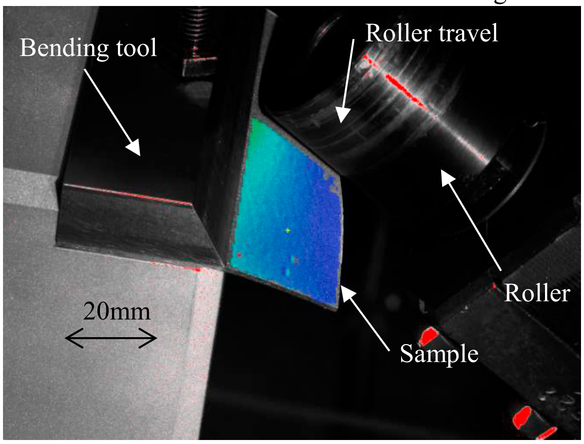


Fig.5(a) Contour plot of major strains

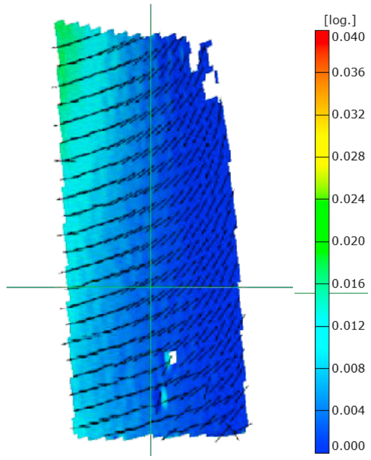


Fig.5(b) Major strain direction The legend in 5b refers to results in 5a and 5b

Fig.6 shows the partitioning of strain within the microstructure of DP1000 as it is deformed in tension.

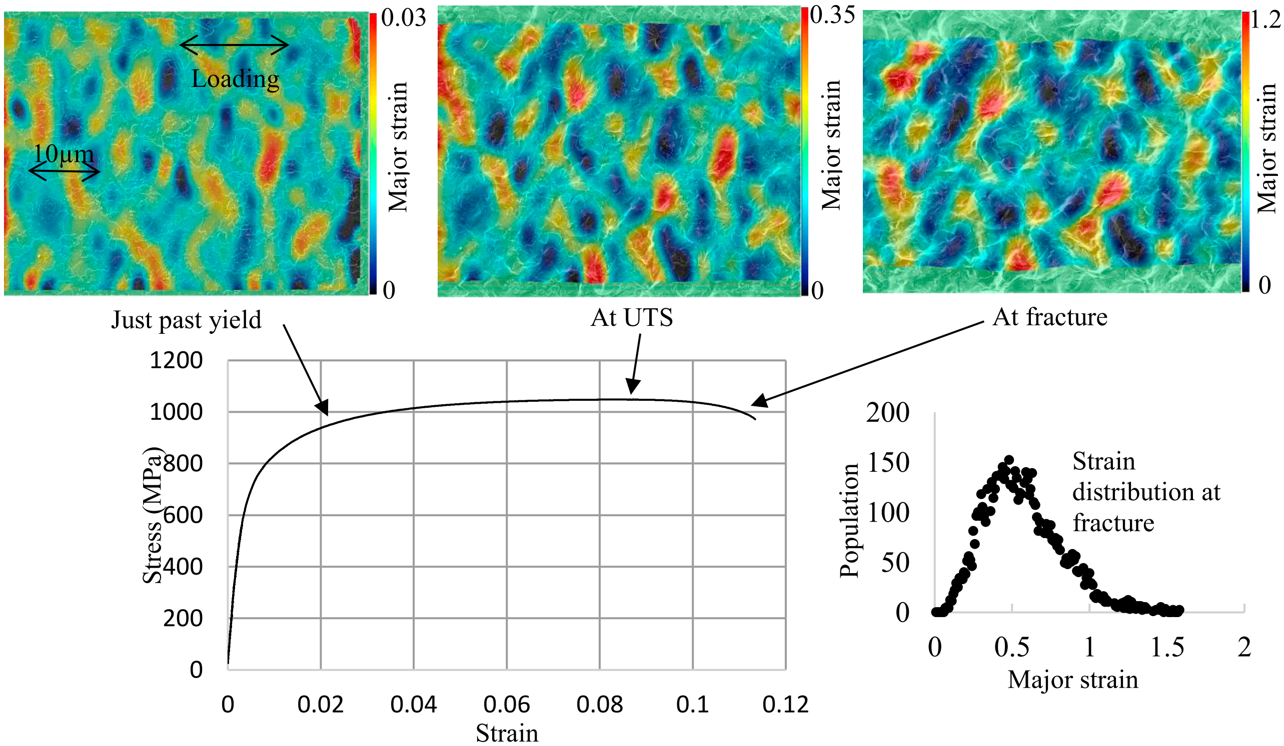


Fig.6 shows the partitioning of strains within the microstructure of the material as it is deformed

The microstructure of the material was made up of a hard martensitic phase and a soft, ferritic phase. Fig.6 shows strain concentrations indicating that deformation occured mainly in the softer, ferrite phase. As the sample was deformed towards UTS, the microstructure was seen to rotate towards its loading direction. At UTS, the strain distribution in the microstructure varied from 0 for the hard region to 0.35 in the soft regions and at fracture the strain distribution is between 0 and 1.5 (Fig.6). Fracture occurred through void growth at the interface between the hard and soft phases.

This study illustrated that incremental bending leads to complex strain fields. When bending is carried out around a tooling surface, frictional forces may act to modify the through thickness strain distribution so that the inner ligament is not compressive as would be expected when the sheet is bent in a free state. While bending is the primary mode of deformation in roll forming, the material is also deformed through shearing along its length, resulting in the material experiencing a three dimensional strain state. In the UHSS grade studied, the complex strain state is partitioned according to the mix of the phases that make up the microstructure with the soft phase exhibiting considerable ductilty. The work suggests two directions of future work. First, the role of longitudinal shear deformation is not well understood and should be given greater importance. Further work could include identifying the factors that influence the degree of shearing and its effect on defects and bendability. Second, it can be speculated that the strain concentrations in Fig.6 that give rise to large strain variations could play an important role in failure of UHSS. Future work may include identifying an optimal microstructure that reduces the severity of the concentrations while still imparting the strength required in-service and the formability required for the roll-forming process.

4. Conclusions

Roll forming forms material through incremental bending, which is a more favourable mode for forming low ductility material. Current work on roll forming has focused on the defects and the residual strains that may cause them. This study looked at measuring the underlying the strain distributions in roll forming that cause these defects in UHSS. Digital image correlation was used to measure macroscopic full-field strains in samples undergoing plane strain bending, incremental bending strains while microstructural strain fields were measured using a Zeiss FEG-SEM and LaVision's DIC software. The results suggested that roll forming leads to the development of a macroscopic three dimensional strain field. While bending is the primary deformation mode, longtidudinal shearing is also significant. Externally applied strains were partitioned at the microstructural level to reflect the distribution of soft and hard phases present in the microstructure. Future work should consider these factors and their influence on the occurrence of defects and fracture.

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